

13 June 2013

**Report to Prince William Sound Citizen's Regional Advisory Council:
Future Iceberg Discharge from Columbia Glacier, Alaska**

Reference PWSRCAC Project #8551

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Report #2

1. Recovery and Inventory of Historic Materials

Time-Lapse Films. Long before the digital time-lapse program was initiated in 2004, film cameras were being used to monitor the glacier's rapid retreat. In 1978-1985, a 16mm film camera maintained by the U.S. Geological Survey (under the direction of Robert M. Krimmel) photographed the glacier front at least once per day uninterrupted for seven years (Krimmel and others, 1985). Then, in 1996-1997, Austin Post and Wendell Tangborn (Hydromet, Inc. of Seattle, Washington) maintained three 35mm film cameras which photographed the glacier terminus, moraine shoal, and Columbia Bay every ten minutes for 16 months as part of the Iceberg Monitoring Project (IMP) research program (Post and others, 1997).

Until recently, the only copies available were low-quality transfers to Video Home System (VHS) tapes, a format with an effective resolution of 0.15 megapixels. Late-production 16mm film copies of the USGS time-lapse sequence have since been recovered from the USGS Washington Water Science Center in Tacoma, and additional 16mm film reels, presumably the camera originals, are currently in the custody of Video Producer Don Becker at the USGS Federal Center in Denver, Colorado. Three 35mm film reels presumed to be the IMP camera originals are currently held by the Valdez Museum. Negotiations are underway with both custodians to produce high quality digital and analog reproductions of the film originals for photogrammetric analysis and scientific archival.

Iceberg Monitoring Project (IMP). The IMP research program (Tangborn, et al, 2000) culminated in a plastic binder with a bound printed report, a series of fourteen Open File Reports (OFR), and a floppy disk with meteorological data (Tangborn and others, 2000). Four complete copies are known to exist - one at the Valdez Museum, one at RCAC's Valdez office, one with Shad O'Neel at the USGS Alaska Science Center, and one with Ethan Welty and W. Tad Pfeffer at the Institute of Arctic and Alpine Research. Digital copies of all available IMP materials will be archived and delivered to the RCAC upon the completion of the current study.

To facilitate frame-by-frame analysis of iceberg drift, the 35mm time-lapse sequences were transferred to 16 inch laserdiscs, a digital format far superior to VHS wherein each frame is stored as a 0.27 megapixel image. Wendell Tangborn recalls sending the laserdiscs to RCAC. If the film

reels held by the Valdez Museum are discovered to be incomplete, finding these missing laserdiscs should be made a high priority.

Finally, iceberg trajectories were derived from the time-lapse photographs using the laser disc reader “by plotting iceberg positions on a 1-km grid overlain directly onto the monitor” (Tangborn and others, 2000, p. 3). However, neither the large notebook that once contained these observations, nor any digital copy of this data, has yet been found.

Additional Materials. A formal agreement was recently struck approving the transfer of Alaskan glacier materials from the USGS Washington Water Science Center to Shad O’Neel at the USGS Alaska Science Center. Among these are the vast majority of film aerial photographs acquired over the Columbia Glacier by the USGS in 1976-2001.

The scanning and processing of these historical stereo photographs can yield information about terminus position, ice surface elevation, and flow velocity, three physically observable quantities that together best describe a tidewater glacier’s geometry and behavior. To further our understanding of the phenomena triggering and regulating Columbia Glacier’s retreat, understanding critical to projections of future behavior, we are making a deliberate effort to assemble this information from all available sources. This includes vertical stereo photographs, oblique time-lapse photographs, LiDAR scans, and TerraSAR-X radar images, described in the previous report, as well as terminus positions gleaned from newly discovered analog maps (Post, 1975; Post, 1982; Post, 1983; Sikonia and Post, 1980).

Our ongoing efforts to assemble time-series of terminus position, ice thickness, and velocity over the full history of the glacier’s retreat are documented in a [Google Spreadsheet](#).

2. Bathymetric Observations

History of Bathymetric Surveys in Columbia Bay. To our knowledge, four rounds of bathymetric measurements have been carried out at or near the Columbia Glacier moraine shoal, from the onset of the USGS research program in 1977 to the hydrographic survey by NOAA Ship Rainier in 2005. Each are described below, followed by a discussion of opportunistic data either known to exist or freshly acquired.

1977-1983

USGS R/V Growler and Bergy Bit

Columbia Bay, moraine shoal, forebay to 1983 terminus

Soundings were collected throughout Columbia Bay and approaches during the summer and fall of 1997 by the U.S. Geological Survey R/V Growler and the radio-controlled Bergy Bit. Taking advantage of a large embayment in the glacier terminus in August - September of that year, soundings were collected outside, along, and just within the moraine shoal. This is the earliest bathymetry on file, but the accuracy of the data is poorly constrained. As Austin Post (1978)

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explains, "tidal adjustments to approximate mean lower low water were made utilizing predicted Cordova tides; spot checks from temporary tide recorders in Columbia Bay indicated these data to be accurate within about 3 feet of measured tides."

Additional soundings were collected in later years in the expanding forebay with the same boat and presumably similar methods. As explained in the Iceberg Monitoring Project (IMP) Open File Report (OFR) 4B by Post and others (1998b), "a preliminary survey of the [forebay] between Heather Island and Tropic Isle was surveyed by the U.S. Geological Survey R/V Growler 1977-1983." A larger scale chart of the moraine shoal bathymetry is provided in IMP OFR 5 (Post and others, 1998a), again citing years 1977-1983 for the earliest soundings in the forebay.

Finally, file BATH in the Krimmel (2001) data report contains "all the bathymetric measurements from Columbia forebay." The soundings are dated either "pre-1985" (presumably the soundings discussed above) or one of 1995-11-26, 1996-09-13, and 1997-10-17 (the soundings discussed below).

1995-1997

Stan Stephens Charters

Forebay to 1997 terminus (partial)

"Stan Stephens Charters, assisted by the USGS in 1995 and by IMP in 1996-1997, obtained water depths in the forebay north of the moraine" (Post and others, 1998a). While R/V Growler surveyed Heather Island to Tropic Isle (the eastern forebay) in 1977-1983, "the remainder of the forebay was surveyed by the Stan Stephens Charters" (Post and others, 1998b). These soundings make up the majority of the BATH file in the Krimmel (2001) data report.

September 5-29, 1994

NOAA Ship Rainier

Columbia and Heather Bays, moraine shoal

National Oceanic and Atmospheric Administration (NOAA) Ship Rainier performed a hydrographic survey of Columbia and Heather Bays up to and including the moraine shoal. The data was published as Hydrographic Survey Sheet H-10567 (NOAA, 1994).

September 1 - October 3, 2005

NOAA Ship Rainier

Moraine shoal, forebay to 2005 terminus

NOAA Ship Rainier returned in 2005 to perform a hydrographic survey of the moraine shoal and forebay up to the glacier terminus. The data was published as Hydrographic Survey Sheets H-11493 and H-11494 (NOAA, 2005).

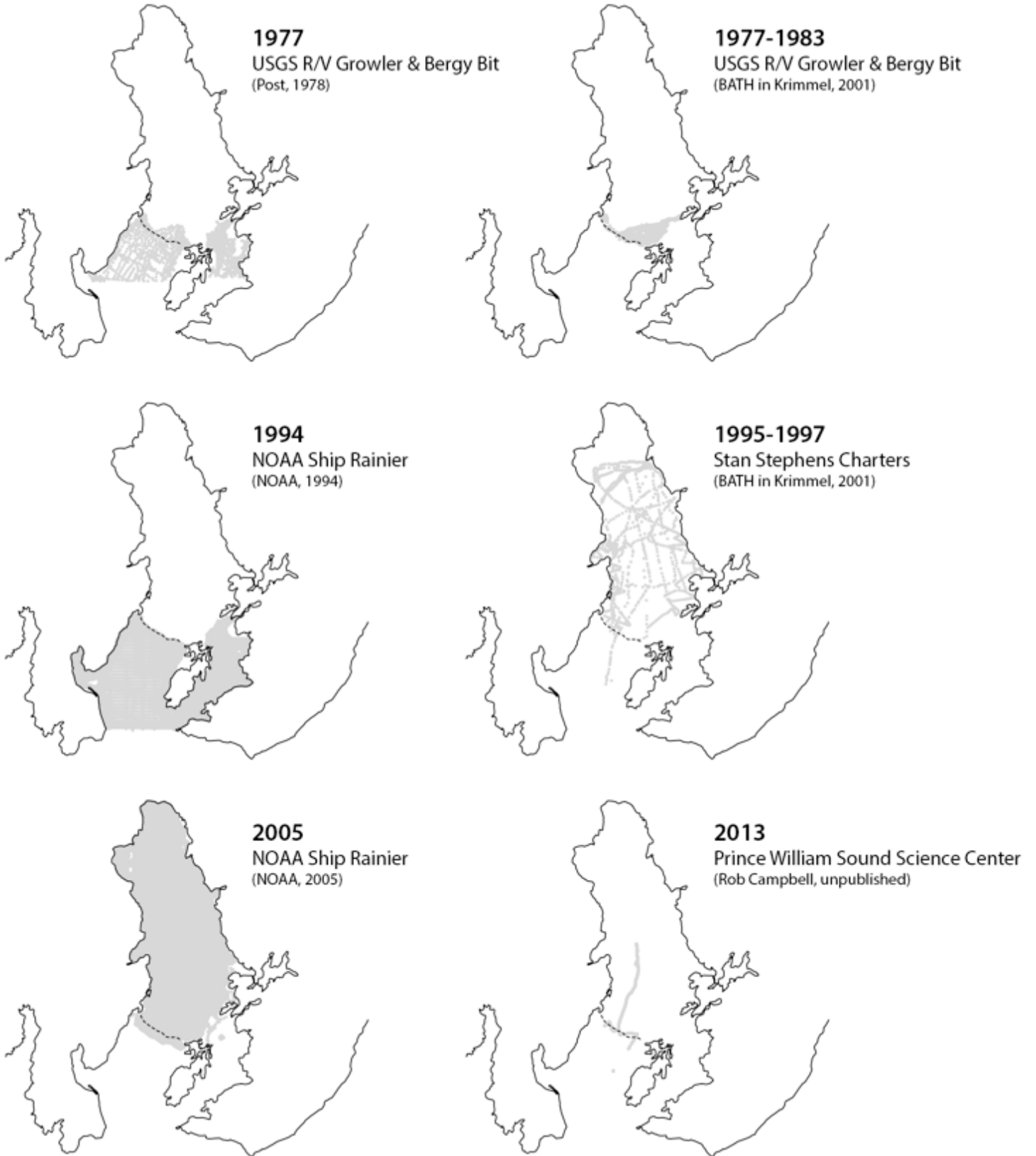
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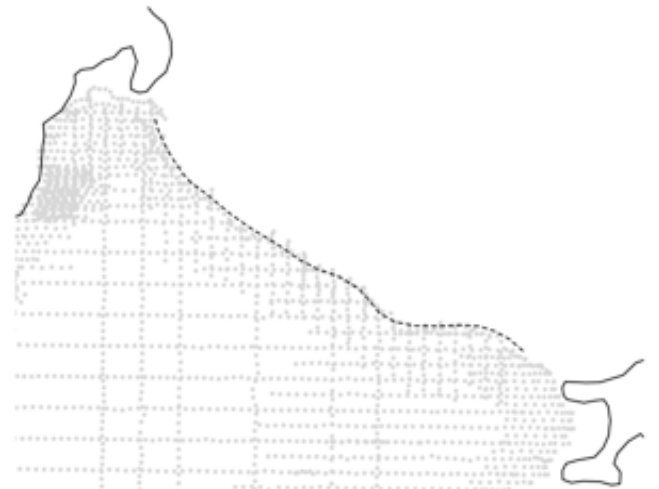
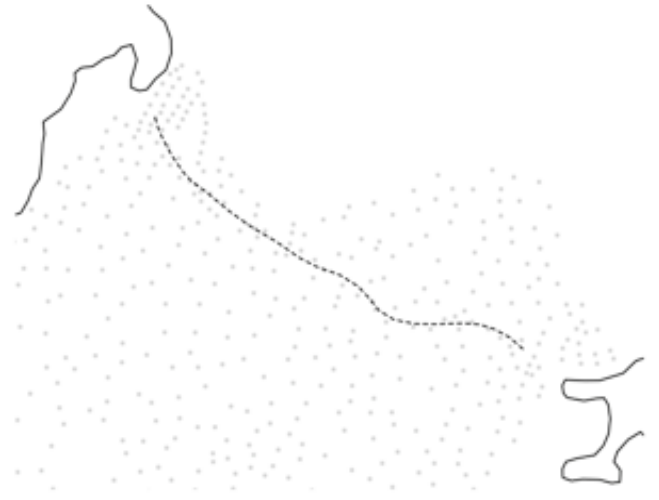
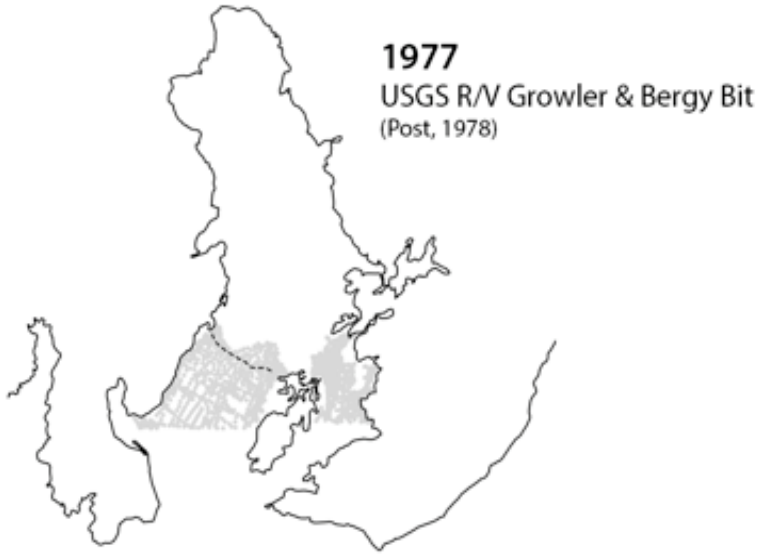
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Rob Campbell (Prince William Sound Science Center) performs bimonthly conductivity, temperature, and depth (CTD) surveys of the Sound. He has generously provided us with depth soundings acquired on 7 May, 2013 in Columbia Bay and along the moraine shoal, and volunteered himself and his boat for a more rigorous and complete survey of the moraine shoal sometime later this summer.

Bernard Hallet (Professor at University of Washington Earth and Space Sciences) is known to have carried out oceanography in Columbia Bay as recently as 2011, but none of his data has been made available to us.

Next 3 pages: *Figure 2-1: Bathymetric surveys, 1977-201; spatial coverage in map view*







1995-1997
Stan Stephens Charters
(BATH in Krimmel, 2001)



2005
NOAA Ship Rainier
(NOAA, 2005)



2013
Prince William Sound Science Center
(Rob Campbell, unpublished)



Bathymetric transects of the moraine crest. IMP Open File Report 5 (Post and others, 1998a) illustrated the changes in the moraine shoal as a longitudinal plot, comparing the 1994 NOAA bathymetry to the 1977 soundings collected by the USGS 15 years earlier.

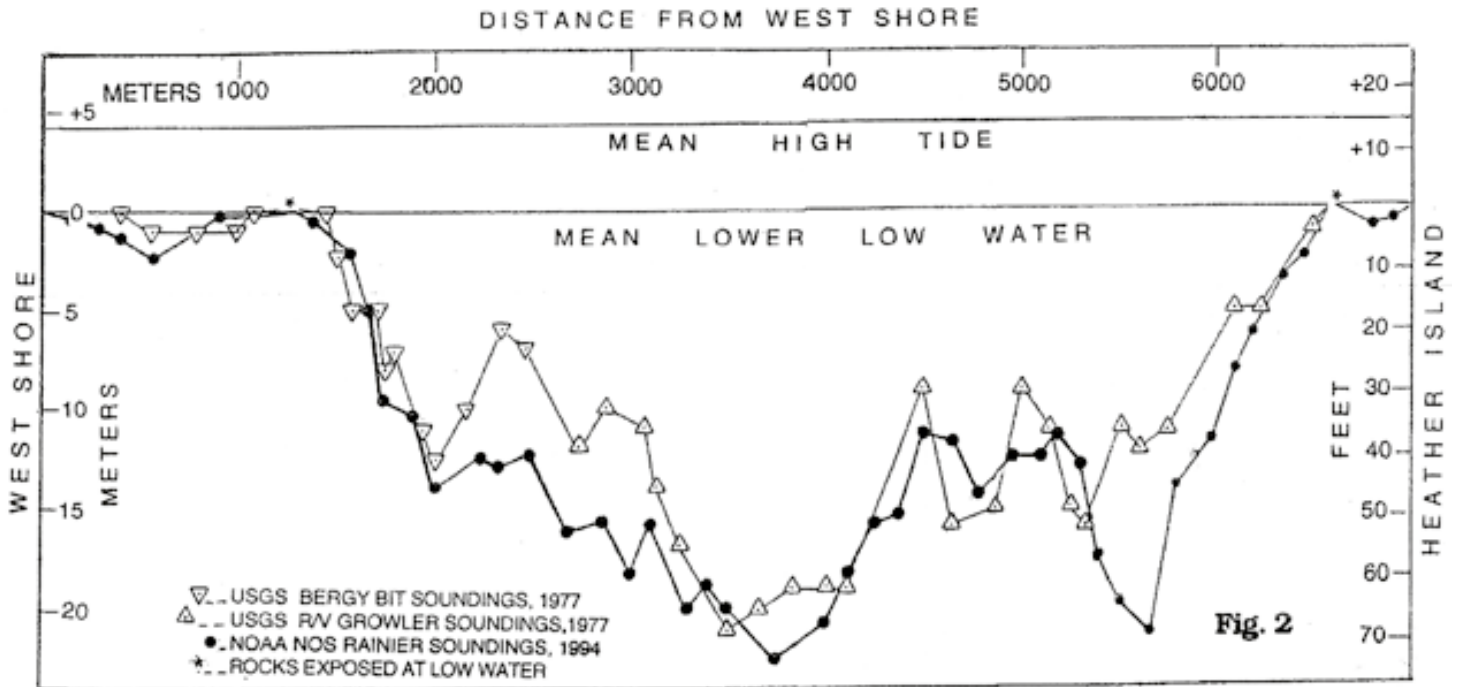


Figure 2-2: Comparison of bathymetric surveys of Heather Bay moraine shoal in 1977 and 1994 (from Post et al, 1998a).

The authors explain the pitfalls of such a comparison, but propose that the apparent lowering of the crest could be real and due to the scouring of the moraine by wave action and current-driven icebergs:

The slightly different positions [and tidal datums] of the soundings may account for most of the variations, except between 2000 - 3000 and 5000 - 6000 meters from the western shore. It is likely that here differences may be due to failure to measure the shallowest water on the crest of the moraine during the course of the surveys due to stranded icebergs. It is also possible that the highest points on the moraine shown in the 1997 surveys have been scoured off by storm waves and tidal current-driven icebergs.

We have recreated the horizontal transect giving rise to the plot, and used it to resample the datasets introduced earlier. In order to correct for the “different positions of the soundings” and to properly sample along the crest of the moraine, the shallowest sounding at each 20-100 m interval falling within 50 m of the transect centerline is used to build each longitudinal profile. Rough agreement between the original figure and the resampled 1977 USGS and 1994 NOAA bathymetry provides a check of transect alignment (each plotted as a pair of lines).

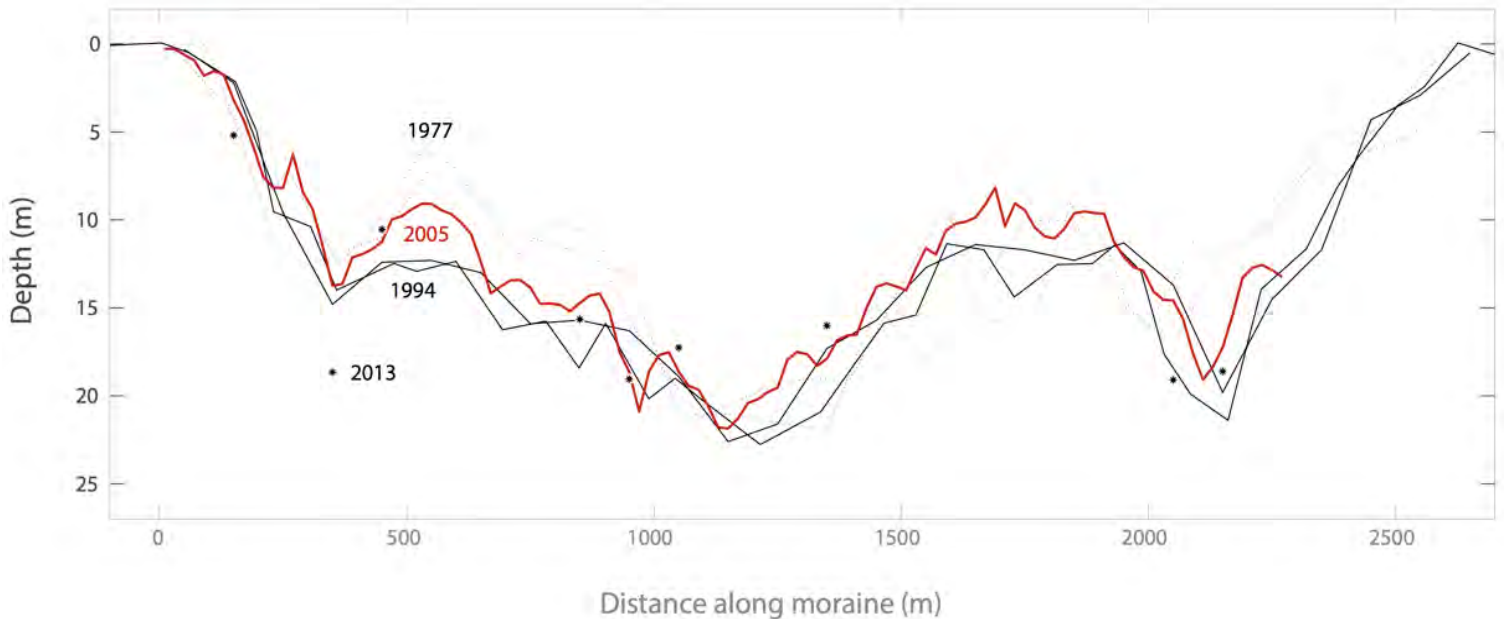


Figure 2-3: Recalculation of bathymetric survey comparison at Heather Bay moraine shoal, 1977 to 1994.

Evidently, the authoritative 2005 hydrographic survey by NOAA Ship Rainier puts to rest earlier suspicions of any major scouring of the moraine shoal. The 10 m spacing between these measurements ensures that the actual crest of the moraine can be reproduced accurately. The overall conclusion of the IMP report remains true today:

For several centuries at least, there has been no major submarine avalanching which could have created deep breaks in the moraine. For the foreseeable future, large icebergs will continue to be trapped by the moraine.

Regional forebay and moraine bathymetry. Comparisons between the 1977, 1994, and 2013 soundings to the gridded NOAA hydrographic survey in 2005 provides a broader view of bathymetric changes. Vertical differences at each point location are colored on a scale expressed in meters per year: black > 0.3 m/yr (shallowing), grey = 0.3 to 0 m/yr, brown = 0 to -0.3 m/yr, red < -0.3 m/yr (deepening). Changes from 1977 and 1994 to 2005 would indicate lowering of the forebay (say, due to the clearing out of fresh, loose glacial deposits) and raising of the moraine crest and distal side (say, due to deposition of scoured sediment). However, the pattern of the 2005 to 2013 changes, measured along the thin, sinuous, but very dense filament of soundings would indicate overall lowering on both sides of the moraine crest.

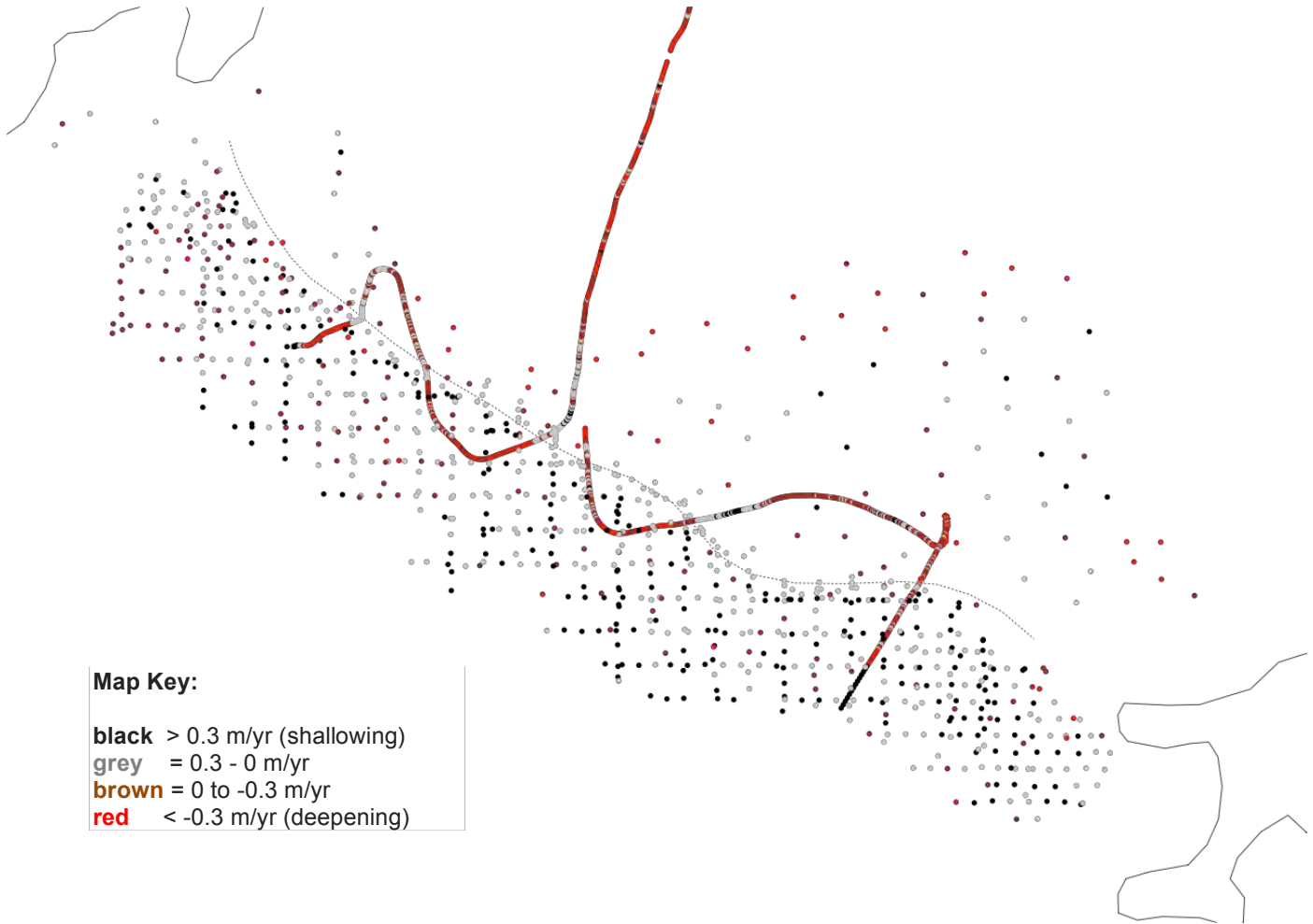


Figure 2-4: Rates of change in bathymetry over survey periods 1977 to 2005, 1994 to 2005, and 2005 to 2013. Data Sources: 1977 USGS R/V Growler and Bergy Bit Soundings (Post, 1978); 1994 NOAA Rainier Gridded Bathymetry (NOAA, 1994); 2005 NOAA Rainier Gridded Bathymetry (NOAA, 2005).

The observed changes are contradictory, and an interpretation, beyond acknowledging the large uncertainties of all but the 2005 survey, is difficult to prescribe. Since the moraine is accentuated by cross-fjord peaks and valleys, and some of these valleys are where currents will be strong, there may be scour and erosion sequences that are spatially limited. The 2005 survey was multibeam, and the raw data is available in the Generic Sensor Format (NOAA, 2005). Looking for textures indicative of scour in the full resolution data, then targeting those locations for a future multi-beam repeat survey may well be the best and only strategy to reconstruct a conclusive narrative of the changes at the moraine shoal.

3. Update on retreat projection

Local (time lapse camera) and satellite (WorldView) imagery have shown several calving terminus embayments, developed over the past several months. These embayments are signs of instability. Visually, the terminus appears to be low in the water, an additional indication of potential instability, and fracturing seems pervasive in regions associated with the main channel and fast flow. Although guided only by intuition, we suspect that there may be an increased potential for a dynamic acceleration in flow, thinning, and calving, perhaps as soon as this summer. A small overdeepening exists upstream of the terminus, and historically, episodes of rapid retreat through overdeepenings have followed periods of temporary stability at pinning points (as is ongoing now). Although we emphasize that this is not a firm prediction for rapid retreat or an abrupt increase in iceberg production, such an event would not be surprising.

Retreat model refinements. The projection model described in Report 1 (December 2012) comprises two alternative procedures, linear and non-linear, for calculating both the future rate of terminus retreat and calving flux, and the time and location of final terminus stabilization after which calving will converge to some steady reduced rate determined by the overall glacier mass balance at that time. Both models are limited to extrapolating past observations into the future, and thus rely on the continued validity of those observations. In the linear model, the average retreat rate over the past decade is assumed to remain true in the future. In the non-linear model, the average thinning rate of the tidewater reach of the glacier over the past decade is assumed to remain constant, and the future calving and retreat rates are calculated from geometric changes driven by that thinning rate. The results of these models are summarized in Table 3-1.

	Linear Model		Non-Linear Model	
Principal Assumption	Fixed Retreat Rate:	0.6 km ³ /yr	Fixed Thinning Rate:	0.02 km/yr
Total Ice Volume Calved (km ³)	52.9		66.2	
Date of Stabilization	2029		2036	
Average Calving Rate (km ³ /yr)	3.11		2.75	
Maximum Calving Rate (km ³ /yr)	5.79		6.2	

Table 3-1: Summary of retreat projection results

Further elaboration of the retreat mechanics beyond what has already been developed in these two models is unwarranted given the weak state of process-derived models for iceberg calving and tidewater hydrological coupling. Extrapolation projections can be robust predictors, however, especially on the comparatively short time scales of interest here (National Research Council, 2012). Our strategy for further model refinement is focused on quantifying the uncertainties in our existing models. The difference between the two projections gives a crude measure of uncertainty, but uncertainties can be quantified in a much more robust fashion by following them from the input assumptions and parameterizations through the calculations to the final projection results. To do this, we will apply formal error propagation analysis and possibly a Bayesian Hierarchical analysis

as well. Table 3-2 lists the variables to be considered in this analysis, with nominal values of those variables as implemented.

Uncertainty analysis of Columbia Glacier retreat models	
Variable	Nominal Value
Position of tidewater limit ¹	km 36
Marine-grounded ice volume	12.77 km ³
Future retreat rate (for linear model)	0.6 km/yr
Future thinning rate (for non-linear model)	0.02 km/yr
Divider Gate initial flux	2.6 km ³ /yr
Divider Gate final flux	2.0 km ³ /yr
Average surface mass balance in tidewater reach	4 m/yr
Instability criterion value (for non-linear case)	1.5

¹: referred to Columbia Glacier centerline coordinate system

Table 3-2: Variables used in retreat projection models to be included in uncertainty analysis

4. Strategy for quantitative iceberg transport model

4.1 Observational constraints

Time-lapse camera AK10 provides an excellent view of the upper reaches of Columbia Bay nearest the glacier. To begin assembling constraints on future iceberg transport models, we are making a qualitative evaluation of the time-lapse sequences from this camera. Daily and sub-hourly interval movies have been constructed using these images, and analysis is underway to extract patterns of iceberg movement. Some of our preliminary findings include: 1) when larger bergs are calved, they undergo a period of limited motion, sometimes for extended (several hours to days) intervals. This is followed by swift exit from the field of view, generally faster than the 20 minute frame rate. These flushing events are associated with rising tides. 2) ice melange tends to flush in very similar ways. 3) The large bergs tend to ground in the near-glacier fjord, likely due to their release from the now narrow central channel, then drifting laterally into shoals. To the best of our knowledge this type of fjord geometry has not been present since the retreat of the terminus from Heather Island. We also have seen several large bergs grounded in the new West Branch Fjord over the time-lapse sequence.

We are also working to develop methods to characterize and quantify iceberg cover in the fjord from the 11-day repeat TerraSAR-X imagery. To date, we have focused on georeferencing of the high quality radar images and developing image processing techniques to automatically determine fractional ice coverage of the sea surface based on radar reflection intensity. A simultaneous effort is underway to compile time series for external forcing, including tides, sea-surface temperature and wind data over the same time intervals.

4.2 Iceberg calving and transport model strategy

Iceberg ocean transport, and degradation during transport, are substantially better understood than iceberg calving processes. Clearly, however, a critical variable in the transport model is the rate and size distribution of the icebergs originally generated through calving. Research on iceberg transport has been motivated by two distinct objectives: the role of icebergs in marine sediment transport, a topic of substantial interest in marine geology, and a now-abandoned effort of the 1970s and 1980s to determine if icebergs could be towed for long distances as a cost-effective source of freshwater for the world's arid regions. Iceberg hazards to shipping and, more recently, to offshore drilling platforms have also provided motivation. The theory and analysis developed in these fields can be applied directly to the down-fjord transport of icebergs at Columbia Glacier. Adapting process models to a statistical framework for iceberg populations characterized by certain size distributions will provide an efficient method for calculating iceberg population distributions at the down-flow (seaward) end of Columbia Bay. As with the uncertainties in the retreat model, an error propagation analysis will be made to determine which of the many variables used has the greatest influence on the final result, and how uncertainties in those variables influence the final projections. The calving and transport process will be broken down into the following stages:

Calving rate and iceberg size distribution. The future total flux of ice (volume or mass per unit time) will be tied directly to the retreat models reviewed in Section 3. Iceberg size distributions have been described both as log-normal (Weeks and Mellor (1978); Morgan and Budd (1978); Dowdeswell et al (1992) and as power-law (Bahr, 1995; O'Neel et al, 2010). The difference between these distributions lies in the smallest size classes, and is thus of concern here, where bergs small enough to be difficult to detect but large enough to damage a vessel are a prime consideration. Either distribution may be correct; a log-normal truncation at smaller sizes could be either an artifact of undercounting small, hard-to-see, bergs or it may be real and a consequence of their rapid degradation following calving, since melt will eliminate smaller bergs more quickly due to their higher area-volume ratio (Dowdeswell et al, 1992).

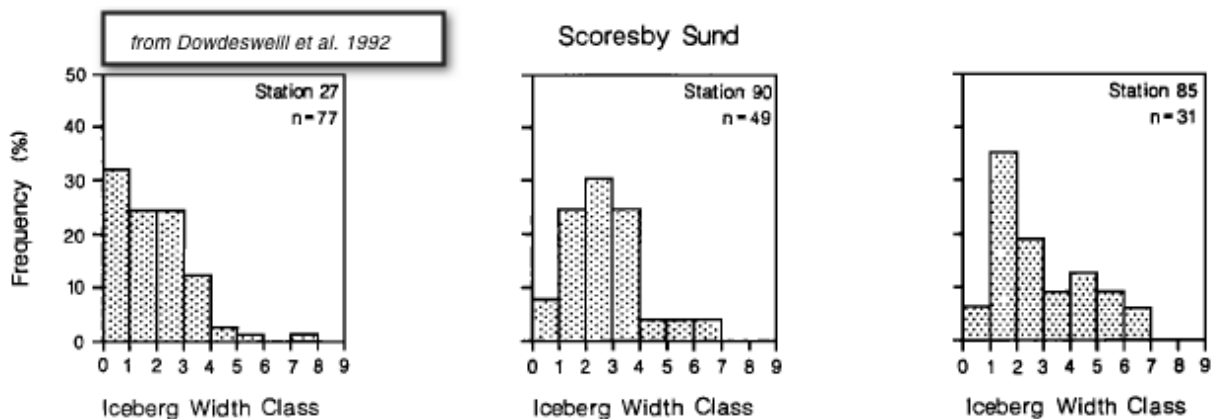


Figure 4-1: Examples of ice size distributions, from Dowdeswell et al, 1992. Station 27 shows a typical power-law distribution, with numbers of bergs increasing monotonically with decreasing size. Stations 90 and 85 show typical log-normal distributions, with frequency declining in the smallest size classes.

Future iceberg size distributions can be generated based on projected total flux and simple assumptions about minimum and maximum berg size. Limits on iceberg size can be obtained from existing imagery, and may be reasonably assumed to be valid in the future, or can be adjusted using simple relationships between berg size and mean terminus ice thickness. Iceberg sizes are abundantly documented in the 1977-2013 catalog of vertical photography at Columbia Glacier, and we are now developing efficient digital methods for measuring berg sizes from the aerial imagery.

Another tool for quantifying size distributions may become available to us through new research being conducted by Tim Bartholomaus, PhD candidate at University of Alaska Fairbanks. Using seismic data gathered by us over the past ca. 8 years at Columbia Glacier, Tim is working on extensions to a seismic filter (originally developed by S. O'Neel and H.P. Marshall at INSTAAR/Univ of Colorado; O'Neel et al, 2007) designed to distinguish iceberg calving from other seismic noise. Tim's research is leading toward algorithms to detect both calving event timing and size (and thus size distributions) from the seismic record. While this tool applies only to observations and has no predictive capacity, it may provide crucial information on size distributions at the time of calving, derived directly from observations. Although much more labor intensive, the size and timing of individual calving events can be extracted from photogrammetric analysis of the time-lapse record, and may be used to spot check the seismic results.

Downfjord iceberg drift. The general equation of motion for an isolated iceberg in the ocean is:

$$M \frac{dV_i}{dx} = -Mf\mathbf{k} \times V_i + F_a + F_w + F_r + F_s + F_p$$

where $Mf\mathbf{k} \times V_i$ is a term describing Coriolis forces and the remaining terms (F) are applied forces arising from wind (a), currents (w), sea-ice drag (s), waves (r), and a pressure gradient force (p) exerted by the water displaced by the iceberg's mass. Several of these terms can be discarded for the situation in Columbia Bay, where the berg motion is not sufficiently steady for Coriolis forces to significantly alter berg trajectories ($f \rightarrow 0$), and where waves are small ($F_r \rightarrow 0$). The pressure gradient force F_p is a transient force that arises during accelerations of the iceberg relative to the water (e.g. during calving or rolling) but may be neglected when calculating long-term transport.

With these simplifications the general equation of motion reduces to:

$$M \frac{dV_i}{dx} = F_a + F_w + F_s$$

The sea-ice drag term F_s may be modified to represent interparticle forces in the sea ice brash that accumulates in the forebay. In the early years of the retreat, brash ice would form a very dense, tightly packed surface layer (ice melange, or Sikkussaq) covering the entire forebay, with large-scale strength properties that had significant effects on iceberg motion. While still occurring in

portions of the forebay today, rafts of brash ice are far more spatially limited and ephemeral than in the past, and it may not be necessary to include this term in projections.

The forces applied by winds and currents will, under steady state conditions, eventually bring icebergs to a steady velocity mostly equal to the current, but with a second-order influence due to wind. If the time scale of this equilibration is short enough, berg motions can be calculated satisfactorily by assuming that they are carried passively by currents, which can in turn be calculated from knowledge of tides in Columbia Bay (Walters et al, 1988) and modeled freshwater discharge from surface mass balance (Rasmussen et al, 2012; O'Neel, 2012). The required time scale of equilibration was calculated by Sodhi and Dempster (1975) as

$$T = \frac{2M}{\rho_w c_w A_w \Delta V}$$

where M is the iceberg's mass, ρ_w is the density of ocean water, c_w is the drag coefficient of the iceberg in water, A_w is the underwater cross-sectional area facing the flow, and ΔV is the velocity change during equilibration. Iceberg motion will thus be determined primarily by currents in Columbia Bay with velocity equilibration time of duration T introduced during current changes. The effect of wind will be difficult to accommodate (since we have no good way of forecasting wind), but some overall correction may be feasible, knowing, for example, that wind near the glacier terminus will be dominated by down-glacier (katabatic) drainage.

Iceberg degradation by melt. Research in the 1970s and 1980s on the feasibility of towing icebergs to arid regions sought to strike an economic balance between the expense of moving the iceberg and the value of the water contained in the ice. Determining the optimal towing velocity proved to be one of the primary challenges: very slow towing cost less in fuel, but the iceberg had more time to melt on the journey. Fast towing not only increased the fuel costs of towing, but may actually have accelerated melt rate through increased forced convection on the submerged iceberg surfaces. In any case, the problems of heat and mass transfer at a submerged iceberg surface were studied intensively during this time (e.g. Weeks and Campbell, 1973; Weeks and Mellor, 1978; El-Tahan et al, 1987; Chirivella and Miller, 1978; Garrett, 1985; Morgan and Budd, 1978; Smith and Banke, 1983), and a number of simplified parameterizations suitable to the present situation were developed. Among these are an empirical expression for the melt rate on the vertical sides of an iceberg (El-Tahan et al, 1987):

$$\dot{m}_v = 2.78T + 0.47T^2$$

where T is the water temperature (degrees C), and \dot{m} is the melt rate (m/yr). In addition, White et al (1980) derived an expression for wave erosion per degree C water temperature at the berg waterline:

$$\dot{m}_{wave} = 0.000146 \frac{H}{P} \left(\frac{R}{H} \right)^{0.2}$$

where P and H are the mean period and wave height, and R is the wave roughness height. The melt rate \dot{m}_{wave} has units of $m/yr/C$.

Iceberg degradation by fracture. An extensive literature exists on the fracture mechanics of glacier ice, but most analyses are too complex to be applied to the thousands of icebergs carried down Columbia Bay. We will adapt some of the more efficient analyses of stability and fracture to our situation, and determine the probability of failure by fracture based on the probability that an iceberg in a given size class will roll and knowledge of the average strength of glacier ice.

Icebergs roll when melt, both above and below the waterline, alters their shape so as to make them gravitationally unstable. Despite the complex and varied geometry of icebergs, the Weeks-Mellor criterion (Weeks and Mellor, 1978) gives a simple but robust indicator of stability. Rolling will occur when:

$$\frac{L_a}{H} = \sqrt{0.92 + \frac{58.32}{H}}$$

where L_a is the iceberg maximum width and H is its total thickness (m). When melt causes an iceberg of a given size to cross this threshold, the berg is assumed to roll, and the internal stresses and time spent in the roll can be calculated from elementary dynamics. These give a rate of loading (approximately the stress divided by the rolling time), and the loading can be compared to measurements of ice strength (e.g. Schulson, 1999). The iceberg size will determine the stress generated during rolling, so not all berg size categories will experience the same rates of degradation by fracture. On failure the iceberg will simply be assumed to split into two smaller bergs of equal size.

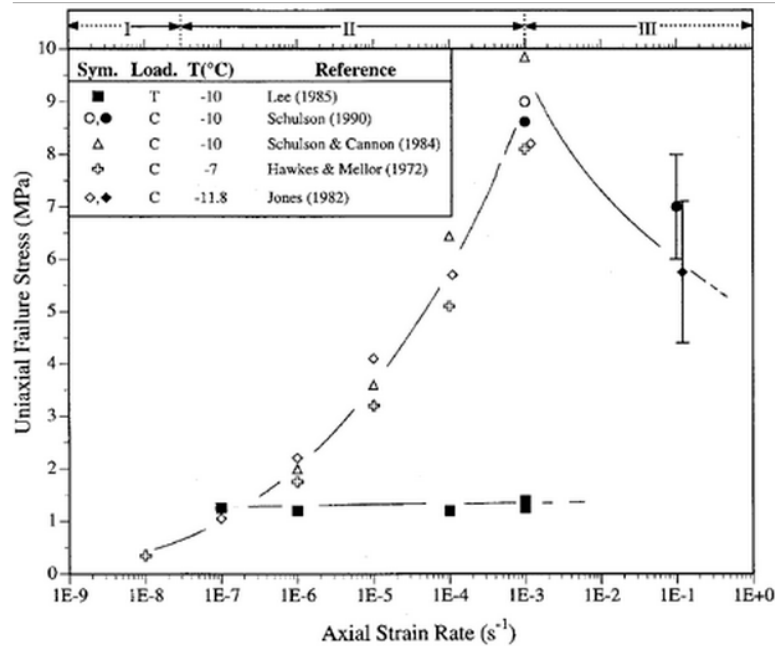


Figure 4-2: Uniaxial failure stress vs. strain rate for polycrystalline glacier ice (from Schulson, 1999)

Iceberg size distribution and passage over Heather Bay moraine. All of the processes described above will generate an evolving size distribution as the iceberg population is advected downstream toward the Heather Bay Moraine shoal. As a means of validation, the down-flow variation of the size distribution can be compared to observations of berg size distribution at positions along Columbia Bay during the course of the retreat. Once imagery has been retrieved from the new Heather Bay moraine camera, the details of iceberg passage over the moraine shoal can be examined in detail. Our current hypothesis is that bergs escape when the water depth over the moraine crest is sufficient for bergs to pass without grounding, and that favorable currents (and possibly winds) are required to move the icebergs. Accordingly, most bergs are hypothesized to escape at some point on the ebb tide, when decreasing water depth and increasing seaward current cross some optimal threshold. Data in the original IMP study will also provide valuable guidance.

5. Heather Island Camera

A digital time-lapse camera was installed inside the USGS cabin on Heather Island on 7 May, 2013. The camera, mounted on one of two survey monuments inside the cabin, is pointed out the window towards the moraine shoal and programmed to acquire an image every 20 minutes (during daylight hours, as determined by a light sensor attached to the camera body). The camera, a Canon 40D equipped with a 24 mm lens, is set to aperture priority (F8) with -1/3 stop underexposure at ISO 200, and loaded with a 32 Gb memory card. The camera clock was synched to Coordinated Universal Time (UTC) by taking photographs of the National Institute of Standards and Technology web clock (www.time.gov) prior to deployment. We verified the system by test-triggering the camera via the camera controller and waiting through three scheduled time-lapse photographs

before departing the cabin. A solar panel was mounted to a tree outside the cabin; the 55 Ah battery had a 13.5 V charge after the power system was connected. A note was taped to the survey monument explaining the reason for the camera and asking visitors to not disturb or remove it.



Figure 5-1: New time-lapse camera installed at the Heather Bay hut (left), and view of moraine (right).

References

- Bahr, D. B. (1995), Simulating iceberg calving with a percolation model, *J. Geophys. Res.*
- Bigg, G. R., Wadley, M. R., Stevens, D. P. & Johnson, J. A. Modelling the dynamics and thermodynamics of icebergs. *Cold Regions Science and Technology* **26**, 113–135 (1997).
- Chirivella, J. E., and C. G. Miller (1978), [In: Husseiny, A.A. (ed.), *Proceedings of the First Conference on Iceberg Utilization for Freshwater Production*. Iowa State University.
- Dowdeswell, J. A., R. J. Whittington, and R. Hodgkins (1992), The sizes, frequencies, and freeboards of East Greenland icebergs observed using ship radar and sextant, *J. Geophys. Res.*, 97(C3), 3515, doi:10.1029/91JC02821.
- EI-Tahan, M.S., Venkatesh, S., EI-Tahan, H., 1987. Validation and quantitative assessment of the deterioration mechanisms of Arctic icebergs. *J. Offshore Mech. Arct. Eng.* 109, 102-108.
- Garrett, C. (1985), Statistical prediction of iceberg trajectories, *Cold Regions Science and Technology*.
- Hock, R., S. O'Neel, and L. A. Rasmussen (2012), Using surface velocities to calculate ice thickness and bed topography: a case study at Columbia Glacier, Alaska, USA, *Journal of ...*
- Krimmel, R. M., Taylor, P., and Barber, P. (1985). *Time Lapse Observations of the Columbia Glacier, Alaska*. 16mm. Tacoma, Washington: U.S. Geological Survey.
- Krimmel, R. M. (2001). *Photogrammetric data set, 1957-2000, and bathymetric measurements for Columbia Glacier, Alaska*. U.S. Geological Survey Water Resources Investigations Report 2001-4089.

- Morgan, V. I., and W. F. Budd (1978), In: Husseiny, A.A. (ed.), Proceedings of the First Conference on Iceberg Utilization for Freshwater Production. Iowa State University National Oceanic and Atmospheric Administration (1994). *Columbia Bay and Heather Bay Hydrographic Survey Sheet H-10567*. NOAA Ship Rainier. Retrieved from <http://www.ngdc.noaa.gov/nmmrview/metadata.jsp?xml=NOAA/NESDIS/NGDC/MGG/NOS/iso/xml/H10567.xml>
- National Oceanic and Atmospheric Administration (2005). *Columbia Bay Hydrographic Survey Sheets H-11493 & H-11494*. NOAA Ship Rainier. Retrieved from <http://www.ngdc.noaa.gov/nmmrview/metadata.jsp?xml=NOAA/NESDIS/NGDC/MGG/NOS/iso/xml/H11493.xml>
- National Research Council, Committee on Sea Level Rise in California, O., Washington, B. O. E. Sciences, Resources, O. S. Board, D. O. Earth, L. Studies, National Research Council (2012), *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*, The National Academies Press.
- O'Neel, S., and W. T. Pfeffer (2007), Source mechanics for monochromatic icequakes produced during iceberg calving at Columbia Glacier, AK, *Geophys. Res. Lett.*
- O'Neel, S., C. F. Larsen, N. Rupert, and R. Hansen (2010), Iceberg calving as a primary source of regional-scale glacier-generated seismicity in the St. Elias Mountains, Alaska, *J. Geophys. Res.*, 115(F4), F04034, doi:10.1029/2009JF001598.
- Post, A. (1975). *Preliminary hydrography and historic terminal changes of Columbia Glacier, Alaska*. U.S. Geological Survey Hydrologic Investigations Atlas 559, sheets 1 & 2. Retrieved from <http://www.dggs.alaska.gov/pubs/id/13645>
- Post, A. (1978). *Interim bathymetry of Columbia Glacier and approaches, Alaska*. U.S. Geological Survey Open-File Report 78-449. Retrieved from <http://www.dggs.alaska.gov/pubs/id/12041>
- Post, A. (1982, December). *Columbia Glacier - 1982 Bathymetry*. Hand-drawn map, scale 1:10,000.
- Post, A. (1983). *Columbia Glacier - 1983 Bathymetry*. Hand-drawn map, scale 1:10,000.
- Post, A., Hallet, B., and Rasmussen, L. A. (1998a). *Bathymetry of the Terminal Moraine Shoal, Columbia Glacier, Alaska*. Iceberg Monitoring Project Open File Report No. 5. Valdez, AK: Regional Citizens' Advisory Council.
- Post, A., Hallet, B., and Rasmussen, L. A. (1998b). *Preliminary Bathymetry of the Forebay, Columbia Glacier, Alaska*. Iceberg Monitoring Project Open File Report No. 4B. Valdez, AK: Regional Citizens' Advisory Council.
- Post, A., Tangborn, W., and Saint Lawrence, W. (1997). *Iceberg Monitoring Project*. 35mm. Valdez, Alaska: Regional Citizens' Advisory Council.
- Schulson, E. M. (1999), The structure and mechanical behavior of ice, *JOM*.
- Sikonia, W. G., and Post, A. (1980). *Columbia Glacier, Alaska; recent ice loss and its relationship to seasonal terminal embayments, thinning, and glacial flow*. U.S. Geological Survey Hydrologic Investigations Atlas 619, sheet 3. Retrieved from <http://www.dggs.alaska.gov/pubs/id/13647>
- Smith, S.D., Banke, E.G., 1983. The influence of winds, currents and towing force on the drift of icebergs. *Cold Reg. Sci. Technol.* 6, 241-245.
- Sodhi, D. S., and R. T. Dempster (1975), Motion of icebergs due to changes in water currents, OCEAN 75 Conference.

- Tangborn, W., Post, A., and Soemarmo, R. (2000). *Mitigating Navigation Hazards from Columbia Glacier Icebergs in Prince William Sound*. Iceberg Monitoring Project Report. Valdez, AK: Regional Citizens' Advisory Council.
- Walters, R. A., E. G. Josberger, and C. L. Driedger (1988), Columbia Bay, Alaska: an "upside down" estuary, *Estuarine, Coastal and Shelf Science*, 26(6), 607–617, doi:10.1016/0272-7714(88)90037-6.
- Weeks, W.F., Campbell, W.J., 1973. Icebergs as a fresh-water source: an appraisal. *J. Glaciol.* 12, 207-233.
- Weeks, W. F., and M. Mellor (1978), Some elements of iceberg technology. In: Husseiny, A.A. (ed.), *Proceedings of the First Conference on Iceberg Utilization for Freshwater Production*. Iowa State University, pp. 45-98.